ASSEMBLY AND TESTING OF A COMPACT, LIGHTWEIGHT HOMOPOLAR GENERATOR POWER SUPPLY

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Summary

Since January 1980, The Center for Electromechanics at The University of Texas at Austin (CEM-UT), funded by the U.S. Army Armament Research and Development Command (ARRADCOM) and the Defense Advanced Research Projects Agency (DARPA), has been developing a high-energy-density, high-current power supply to drive an electromagnetic (EM) railgun. Achieving high energy density, which implies a compact, lightweight device, is required if EM accelerators are to become practical, field-portable systems. The initial step in developing the power supply was to design, fabricate and test a prototype homopolar generator, attempting to improve the state of the art in energy and power density. This step was completed in August 1982. Utilizing the All-Iron-Rotating (A-I-R) configuration, which eliminates the back-iron of previous machines, the prototype compact HPG inertially stores 6.2 MJ and weighs 3400 lb_m, a state-of-the-art gain in energy density of a factor of two. During initial tests, the HPG generated a 1.02 MA current pulse. Analysis indicates that one compact HPG will drive an 85-g projectile to 3 km/s in a 4-m gun or a 10-g projectile to 10 km/s in a 5.5-m gun. The machine is currently being upgraded, and a compact inductor is being built to provide a load. This paper summarizes the machine design, presents results of the initial test sequence, and briefly discusses the continuing CEM-UT program to develop a high-energy-density, high-current EM railgun power supply.

Machine Design

For the prototype of a compact HPG, the A-I-R HPG configuration was implemented into a machine design which has a small stator and utilizes developed state-of-the-art components (Fig. 1). Figure 2 summarizes the characteristics and physical size of the generator. Key design issues and their solutions were as follows:

- since radial thickness of the inner brush mechanism and field coil reduce the flux-cutting area, and hence the terminal voltage, a radially thin brush mechanism, and an uncooled pulsed field coil were designed;
- armature reaction was addressed by testing the machine first with an unclad rotor (presented here) and providing for a copper-clad rotor if required;
- field portability dictated rolling-element bearings, which have minimal hydraulic requirements. The bearings were accommodated by insulating and shielding them from stray magnetic fields;
- for this design to be feasible, a disassembleable rotor with insulation between rotor halves was required. This was accomplished using a 60,000-psi hydraulic assembly technique and ceramic insulation;
- a 750-kA making switch, an expensive component, was eliminated by using the brushes to close the output circuit.

These design issues were discussed in detail in a paper presented at the last Pulsed Power Conference.[1] A unique feature of this machine is that one can easily connect the rotor halves electrically in parallel rather than in series, which results in 25-V, 1.5-MA output characteristics without increasing component performance levels.

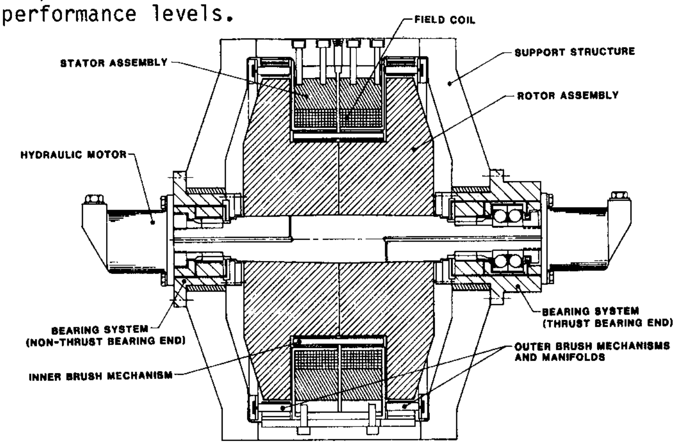
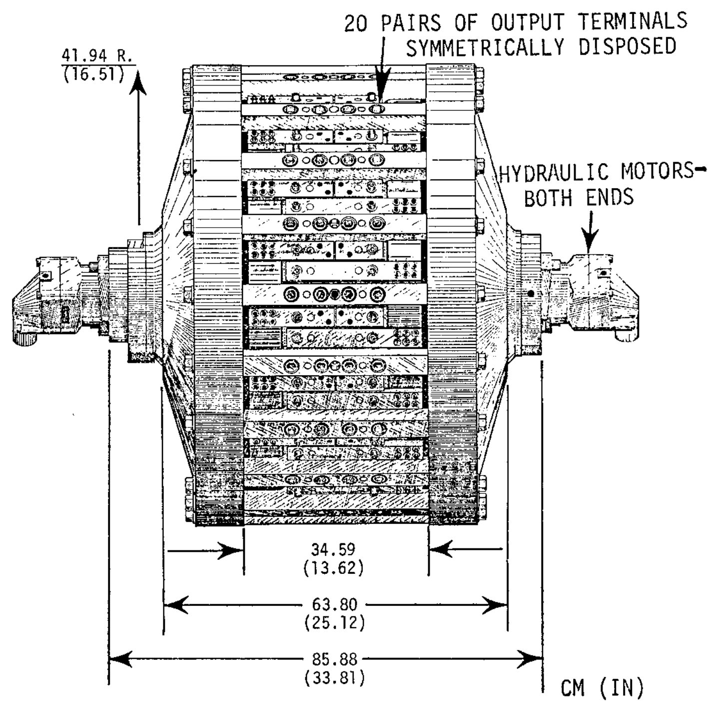


Fig. 1. Section through compact homopolar generator



Stored energy - 62 MJ at 6,245 rpm	Terminal voltage - 50 V at 6,245 rpm
Effective machine - capacitance - 4,960 F	Internal resistance - 7.6 μΩ
	Internal inductance - 30 nH
Rated discharge current - 750,000 A	Total generator weight - 1,545 kg (3,400 lb_m)

Peak discharge torque - 61,000 N·m (45,000 $ft\text{-}lb_f$) (at rated current)

Fig. 2. Dimensions and performance parameters of the compact homopolar generator

The compact HPG is designed to store 6.2 MJ, have approximately a 5-kF capacitance, and generate 750 kA. In initial tests of the machine, these design goals have been reached or exceeded. The rotor was motored to 6,400 rpm, slightly faster than the 6,250-rpm design speed, in 2 min, and stored 6.5 MJ inertially at the higher speed. Because of a current constriction in the

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dump resistor load, the maximum energy transferred was from 5,450 rpm (4.7 MJ) during a 370-kA discharge. In a short-circuit test from 1,360 rpm, however, the machine generated 1.02 MA, 36 percent higher than the design level. At this current level and with the fast current rise time (15 ms to peak), the internal resistance was 10 μΩ. There was no significant armature reaction. The experimental machine components -- including rolling-element bearings, disassembleable rotor, pulsed field coils, and a combined current collection and making switch system -- all performed successfully.

To summarize the initial test results:

- 74 discharges were completed.
- Mechanically, the machine performed as designed. The rotor was motored to 6,400 rpm -- 150 rpm faster than rated -- in 2 min, as designed. No bearing problems due to stray magnetic fields were encountered.
- 1.02 MA -- 270 kA more than rated -- were generated from 1,360 rpm.
- From 5,450 rpm (4.7 MJ stored in the rotor) 370 kA were generated. The load voltage was 34 V. This was the highest energy discharge.
- A 1.75-T magnetic field resulted from 432 A in the pulsed field coil. An open-circuit voltage of 47 V at 6,250 rpm was extrapolated at this field level. It should be possible to reach the design field level of 2.0 T by increasing the power supply output. A 600-A excitation current was achieved during initial field coil tests.
- The inflatable brush actuators continued to work throughout the tests, even though several of the actuators were later found to have ruptured.
- An internal resistance of 10.9 μΩ -- 3.4 μΩ more than estimated -- was calculated for a 750-kA discharge. This difference was a result of the current not penetrating into the rotor because of the fast rise time. For a fully penetrated rotor, a 5.75-μΩ internal resistance is estimated, based on data for a 1.02-MA discharge.

Non-rotating Tests

After HPG module assembly, tests were conducted to determine the effect of the magnetic field on the rolling-element bearings. This was important because of the possibility that the field would increase the operating torque of the bearings, which would have required immediate major reworking of the bearings. No problems were encountered, however. With no magnetic field, the torque required to spin the rotor was initially 12.1 N•m. When the rotor was rotated by hand with full magnetic field, the torque was increased to 13.6 N•m. This was an acceptable result because at full magnetic field the bearings experience full loads from the magnetic tilt force and negative-spring-constant axial force.

Rotating and Open-Circuit Voltage Tests

Initial rotating tests were designed to evaluate bearing and motoring performance and to seat the brushes. The rotor was motored to a low speed and the brushes were actuated. From 500 rpm, the brushes stopped the rotor in 0.7 s. The next series of tests preceded an open-circuit voltage measurement from which the average magnetic field strength could be determined. First, the rise time of the magnetic field was monitored. It took approximately 2 s for the magnetic field to rise, and the field buildup lagged the excitation current rise by 0.2 s. The rotor was then motored and allowed to coast, with and without magnetic field. There was no significant change in the coasting characteristics with magnetic field. The first open-circuit voltage test was from 463 rpm, the machine potential being 3.8 V. No current flowed in these tests because no load was connected to the terminals. Given that

$$V = \frac{\omega\phi}{2\pi}$$

where V = open-circuit voltage = 3.8 V
ω = rotational speed = 48.5 rad/s
ϕ = flux linkage, Wb,

for two voltage generating paths

$$\phi = 0.246 \text{ Wb} .$$

Since

$$B \text{ (flux density)} = \frac{\phi}{\text{magnetic area } (0.13 \text{ m}^2)}$$

$$B = 1.9 \text{ T} .$$

On the next run, open-circuit voltage was monitored. At 1,087 rpm 8.3 V were measured, indicating an average magnetic field strength of 1.77 T.

Discharge Tests

Discharge tests with a constant magnetic field (1.77 T) were conducted at incrementally increased speeds. Figure 3 is a graph showing voltage vs rpm. The design open-circuit voltage of 50 V was not realized because the tests were conducted at 1.75 T rather than 2.0 T. This was because the particular field coil power supply being used could not be easily adjusted, and is not an inherent problem with the HPG. In Fig. 3, note the voltage drop internal to the HPG, which represents the machine's internal resistance.

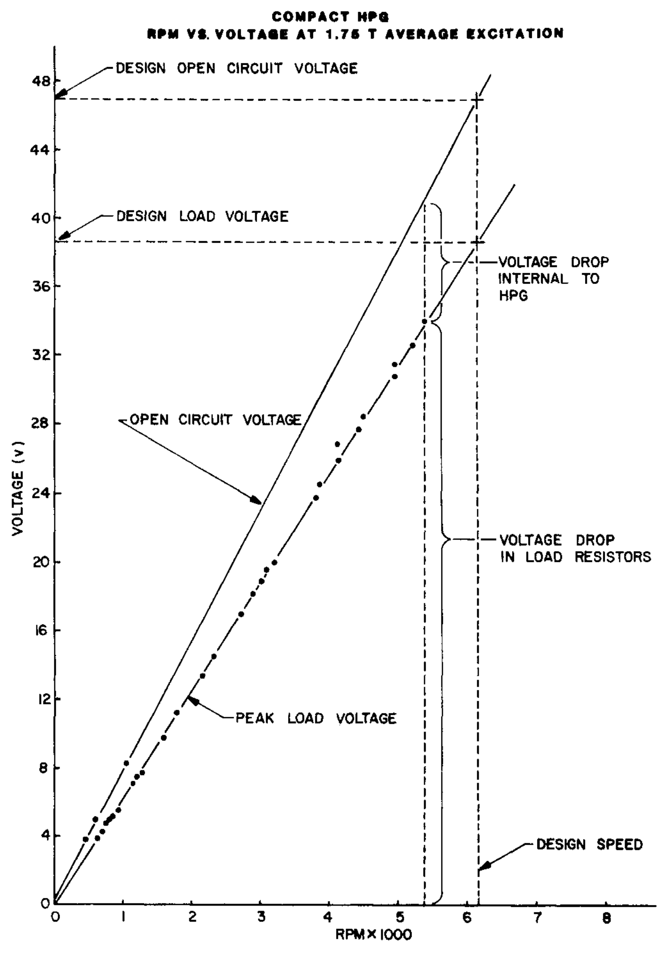

Fig. 3. HPG output voltage vs rotor speed

Figure 4 is a graph of peak load voltage vs discharge current.

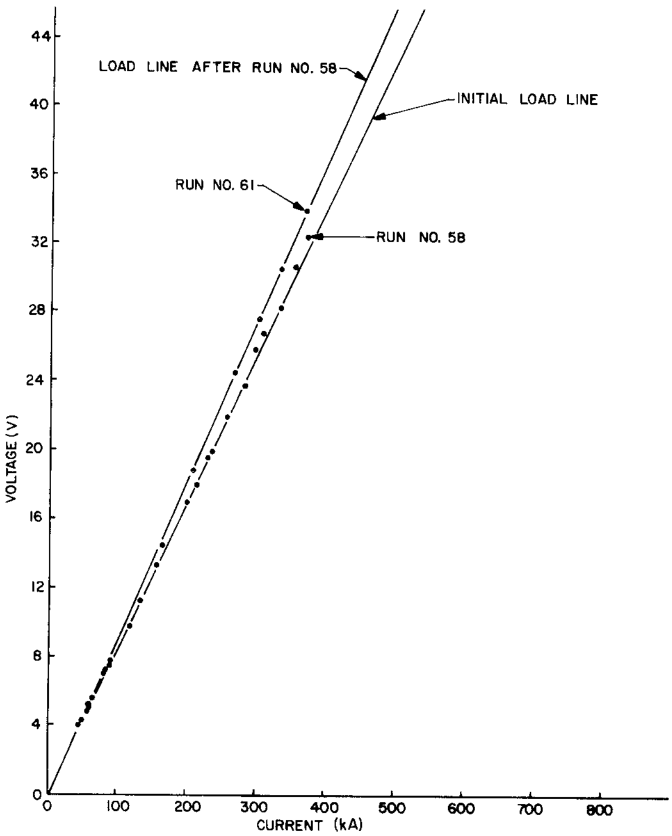

Fig. 4. Peak load voltage vs discharge current.

Run No. 58 consisted of motoring to 5,500 rpm and discharging from 5,265 rpm. The machine generated 375 kA from a 32.6-V load potential. Run No. 61 consisted of motoring to 5,700 rpm and discharging from 5,435 rpm (see Fig. 5). The machine established the correct voltage for this speed, 34 V, but generated only 370 kA. Note the 20-kA current break-up that occurred 20 ms into the discharge.

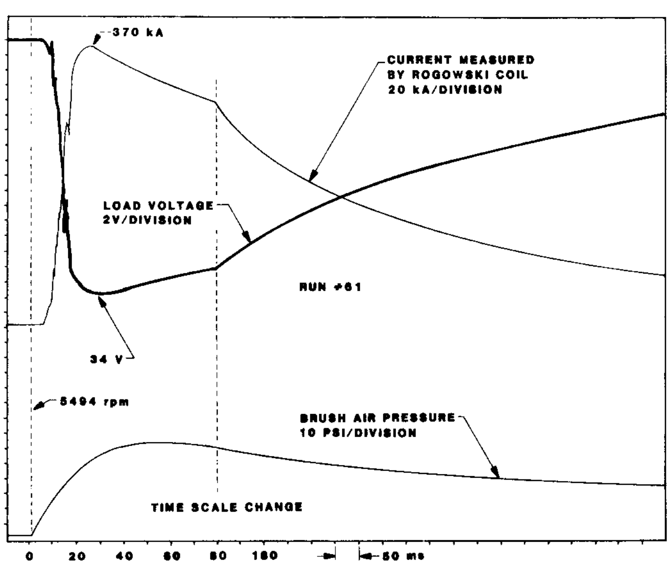

Fig. 5. Performance of HPG during Run No. 61

After several lower-speed runs, it was clear that a new load resistance was in effect (see Fig. 4). The cause of the added resistance could have been internal to the machine, such as a deteriorated contact, or there could have been a a change in the properties of the load. On both the 5,265-rpm and 5,450-rpm discharges the load resistors became very hot at a current restriction caused by two incorrectly positioned bolt holes. Overheating of the resistors was a matter of concern because if several resistors were to melt during a discharge, a thermal runaway would be possible. One resistor after another would melt and arc. Therefore, the decision was made to attach shorting bars across the machine terminals and to attempt a series of low-speed, full-current discharges.

Before proceeding to these tests, the mechanical performance of the machine needed to be verified. On two successive attempts to reach full speed, the displacement limit of the hydraulic motoring pump was reached. After adjusting the pump, the rotor was spun to 6,400 rpm in 124 s. This was 150 rpm faster than design speed, and the motoring took 4 s longer than estimated. At 6,400 rpm, the rotor was still being accelerated rapidly, however, and higher speeds can definitely be obtained. During the full-speed tests, no vibrations were encountered other than a slight vibration at 1,800 rpm, which was excited by the prime-power 200-hp electric motor. All tests of the system were conducted without bolting the torque frame or the HPG to the floor.

After conducting the full-speed mechanical tests, the stainless steel dump resistors were removed, and twenty copper shorting bars were clamped across the machine terminals, readying the machine for low-speed, full-current tests. While removing the stainless steel dump resistors, several partially-melted resistors were found, including one resistor that had melted through. The damage to the resistors accounted for the new load line that came into effect after Run No. 58 and the previously-noted current break-up that occurred during Run No. 61. Some of the higher-than-calculated circuit resistance can be attributed to contact drop between the stainless steel and copper (the stainless steel was neither flat nor flexible) and the decreased conductor area at the improperly drilled bolt holes.

Short-circuit tests of the HPG were very successful. Generation of high currents results in full electromagnetic forces and tests the ability of the bearings, brushes, and conductors to withstand these forces. Eight low-speed, high-current discharges were carried out at increasing current levels of 250, 435, 650, 740, 825, 790, 880 kA. Finally, from a speed of 1,360 rpm, 1,020 kA was generated. Oscillograph traces of this discharge showed that the current rose cleanly to a peak in approximately 20 ms (see Fig. 6).

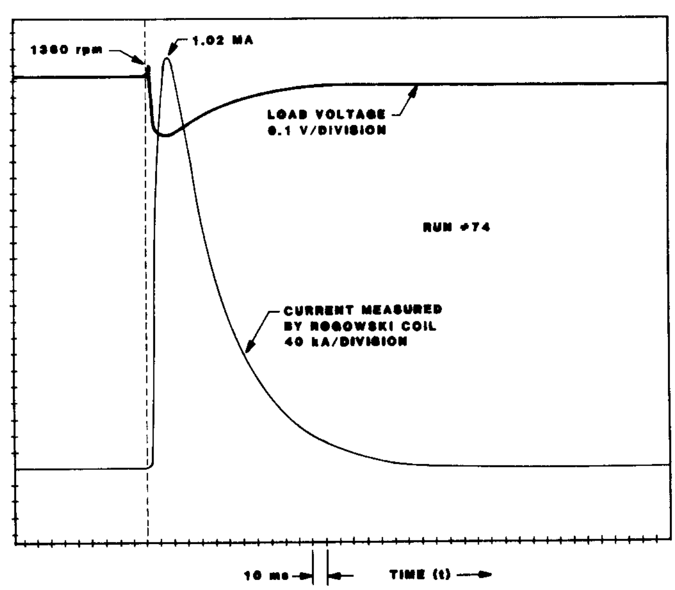

Fig. 6. Output current vs time

The 1.02-MA discharge was 36 percent more than the machine was rated to generate, and the discharge torque was apparent. Since the machine was not bolted down, it was raised off the floor. It can be concluded that with a refurbished brush mechanism, reground slip ring, and a larger air gap, the compact HPG will be capable of operating at substantially higher currents than achieved thus far.

Because the machine terminals were essentially shorted, the high-current tests produced the best data for calculating the effective internal resistance of the machine, which includes armature reaction, brush contact drop, and component resistive drops. Since the rate of rise of the current for these initial discharges into a resistive load was fast compared to the time constant of the magnetic circuit, there was not enough time for armature reaction to become a problem. The internal resistance of the machine without armature reaction is valuable information, however, since it will permit a direct calculation of armature reaction if it should occur in future tests.

Note that the effective brush resistance varies inversely with current, since the voltage drop across the brush is essentially constant. The effective internal resistance with no armature reaction but full current penetration into the rotor was originally estimated to be 7.5 $\mu\Omega$ for a 750-kA discharge.

The discharge closest to the 750-kA machine rating was the 740-kA discharge from 1,064 rpm. The current peaked in 15 ms, the voltage drop across the shorting bars was 0.26 V, and the open-circuit voltage was 8.3 V. For this discharge, the effective internal resistance was calculated:

$$R_{int_{eff}} = \frac{8.3\ \text{V} - 0.26\ \text{V}}{740{,}000\ \text{A}}$$

$$= 10.9\ \mu\Omega.$$

This resistance is not for a fully-penetrated rotor, however. The depth of penetration of the current for 15 ms to current peak was calculated:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} = 6.16 \times 10^{-3}\ \text{m (0.243 in.)}$$

given $t/4$ = time to peak = 0.015 s
t = 0.06 s
f = frequency = $1/t$ = 16.7 Hz
μ = permeability of steel at 2.0 T = $53 \times \mu_o$ = 6.66×10^{-5}
σ = conductivity of steel = 7.4×10^6 mho/m.

For this depth of penetration, the resistance of one rotor half was calculated:

$$R \simeq 1.1 \times 1/(2\pi w\sigma)\ \ell n\ (r_o/r_i)$$

given w = width = depth of penetration = 6.16×10^{-3} m (0.243 in.)
r_o = outer rotor conductor radius = 33.7 cm (13.26 in.)
r_i = inner rotor conductor radius = 19.2 cm (7.57 in.)
R = 2.11 $\mu\Omega$/rotor half.

Using this information, the effective internal resistance of the HPG charging an inductor with 750 kA and no armature reaction was calculated:

$$R_{int_{eff}} = 10.9\ \mu\Omega - 2 \times 2.11\ \mu\Omega + 2 \times 0.055\ \mu\Omega$$

$$= 6.79\ \mu\Omega,$$

where R = 0.055 $\mu\Omega$ for a fully-penetrated rotor. This compares well with the original 7.5-$\mu\Omega$ resistance estimate.

The short-circuit, 1.02-MA discharge was from 1,360 rpm, which from the plot had a 10.4-V open-circuit voltage. The voltage drop across the shorting bars was 0.34 V. Therefore,

$$R_{int_{eff}} = \frac{10.4\ \text{V} - 0.34\ \text{V}}{1.02 \times 10^6\ \text{A}}$$

$$= 9.86\ \mu\Omega.$$

Since the current rise time was the same as during the 740-kA discharge (15 ms), depth of penetration (6.16×10^{-3} m) and rotor resistance (2.11 $\mu\Omega$/rotor half) are also the same. The effective internal resistance for a fully-penetrated rotor conducting 1.02 MA and having no armature reaction was calculated:

$$R_{int_{eff}} = 9.86\ \mu\Omega - 2 \times 2.11\ \mu\Omega + 2 \times 0.055\ \mu\Omega$$

$$= 5.75\ \mu\Omega.$$

Disassembly and Upgrading

Disassembly of the machine verified that the components had performed as designed. The brushes and slip rings were in satisfactory condition although some signs of arcing and burning were observed, significant amounts of copper were deposited on one outer slip ring, and several brush actuators had ruptured. The rotor was disassembled easily in 45 minutes, the bearings were in good condition, and the machine was structurally intact.

In preparation for the next test sequence, in which the HPG is to be used to charge an inductive load, the machine was upgraded. New brushes which were carefully fabricated for precise positioning were installed, and actuators with twice as much travel and down force were developed. In addition, the armature conductor thickness was increased to 1/4 in., and the conductors were machined to fit the stator, thus resolving a previous stator thickness tolerancing problem.

Continuing CEM-UT Program

Several parallel efforts are underway at CEM-UT to continue to advance the state of the art of high-energy-density, high-power HPGs. The upgraded prototype compact HPG will be tested using an inductive load.[2] Initially, a 50-percent energy transfer (3.1 MJ) at 1.0 MA will be attempted. If successful, the current level will be increased until a limit is encountered. A single-shot opening switch and a railgun will be designed and built, completing the prototype compact EM railgun system. At the same time, an HPG system tester[3] has been built and is being used to develop components for an even higher-energy-density, higher-power HPG. These components include cooled brushes of both face and rim types and a stationary-shaft hydrostatic bearing. Utilizing results from these efforts, a complete field-portable second-generation compact EM railgun system will then be designed and built.

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